SEALING LARGE DIAMETER CAST-IRON PIPE JOINTS UNDER LIVE CONDITIONS

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Natural Gas Infrastructure Reliability Industry Forum – U.S. Department of Energy

- **Project Objective – Develop a Robotic System for Internally Sealing Multiple Cast-Iron Bell and Spigot Joints from a Single Pipe Entry**

- **Participants:**
  - **- Funding: NETL DOE (80%) and GTI (20%)**
  - **- Gas Technology Institute (contractor)**
  - **- Maurer Technology Inc. (subcontractor)**

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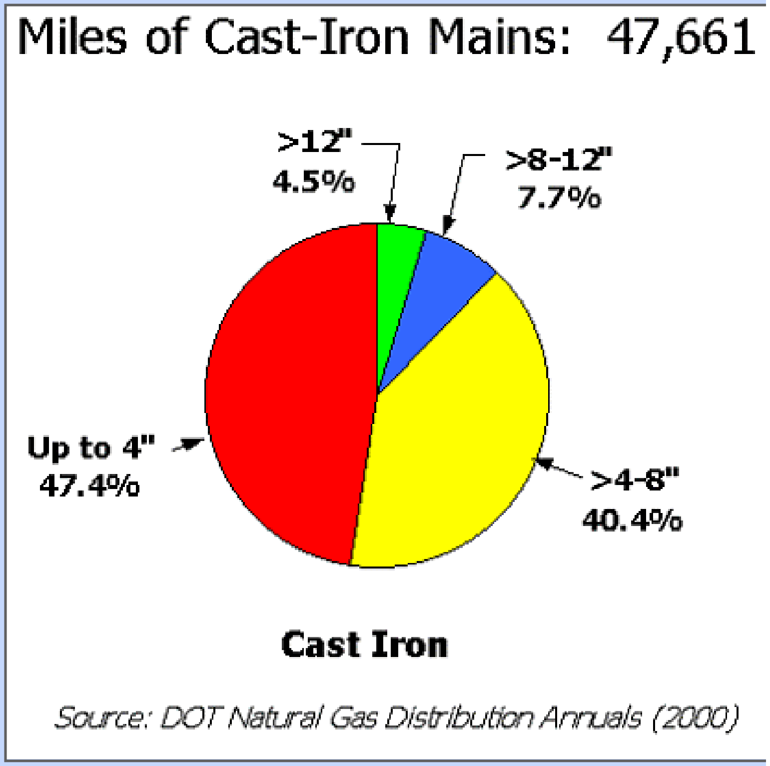
Problem Summary

- Over 47,000 miles of cast-iron gas mains are in service in USA
- Bell and spigot joints can leak due to drying out of jute (accelerated by use of dry natural gas)
- Conventional repair methods (external encapsulation or installing repair sleeves) are expensive and disruptive



Benefits of Proposed Robotic Repair

- Extends operating life of cast-iron gas mains
- Approach greatly reduces excavation requirements
- Pipe remains in service; no interruption of gas delivery
- Expected savings of 25 – 35%
- Single system can operate in wide range of pipe sizes

Project Timeline & Schedule

- Work initiated March 25, 2002
- Project consists of 11 tasks conducted over 24 months
- 1^{st} quarter activity completed
- Reporting on Tasks 1 – 5

Project Tasks

- Program Management
- Establishment of Detailed Design Specifications
- Design and Fabricate Ratcheting Stainless-Steel Repair Sleeves
- Design, Fabricate and Test Patch-Setting Robotic Train
- Design and Fabricate Pipe Wall Cleaning Robot Train with Pan/Tilt/Zoom Camera
- Design and Build Surface Control and Monitoring System

Project Tasks

- Design and Fabricate Large-Diameter Live Access System
- System Integration and Laboratory Validation
- Field Testing and System Refinement
- Benefits Analysis
- Final Report

Major Issues for Internal Repair

- Misalignment of joints
- Variation of inside pipe dimensions
- Presence of debris and standing water
- Missing/damaged jute
- Drip pots and other obstructions

Components of Joint-Sealing System

- Pipe-access hardware for entering gas main
- Two multiple-module robot trains
  - Inspection/Joint Cleaning Assembly
  - Patch-Setting Assembly
- Coiled-tubing delivery system for locomotion and communication
- Surface control and display electronics

Basic Operational Process

Step 1: Excavate short section of gas main

Step 2: Attach entry fitting to pipe and pressure test

Step 3: Cut hole into pipe through fitting

Step 4: Introduce inspection/joint cleaning assembly into pipe

Step 5: Push assembly to farthest bell & spigot joint to be repaired

Step 6: Clean farthest joint and visually inspect

Step 7: Pull assembly back to next joint and clean

Step 8: Repeat until all joints are clean and ready for patching

Basic Operational Process

Step 9: Withdraw inspection/joint cleaning module and replace with patching module

Step 10: Push assembly to farthest joint and align patch with joint

Step 11: Inflate expander bladder with N_2 to lock steel sleeve to support patch as it cures

Step 12: Deflate bladder to release assembly

Step 13: Withdraw patching assembly from pipe and load a fresh patch

Step 14: Push assembly to second joint & align patch

Step 15: Repeat until all joints are patched

Step 16: Repeat entire process in opposite direction

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Discussion Topics

- Pipe Access
- Joint Preparation
- Joint Patching
- Locomotion
- Upcoming Work

Entry Fitting Functions & Attributes

- **Support "hot tapping" of pressurized gas mains**
- **Restore mechanical competence of pipe "lost" from hot-tapping procedure**
- **Provide controlled, no-blow entry and removal of repair system**
- **Provide long-term, leak-free operation**
- **Resist pull-out and detrimental aging**

Entry Fitting – Design Considerations

- **Size and weight**
- **Exterior surface condition of cast-iron pipe**
- **Field installation procedures and tests**
- **Seal effectiveness and redundancy**
- **Re-useable**

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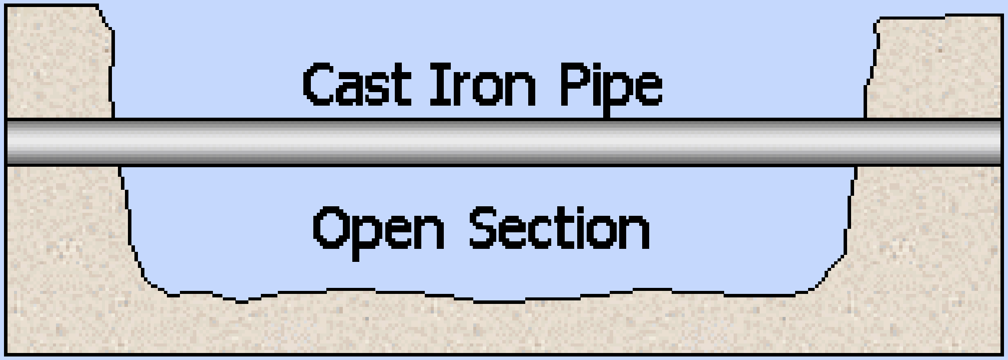
Entry Fitting – Mathematical Analyses

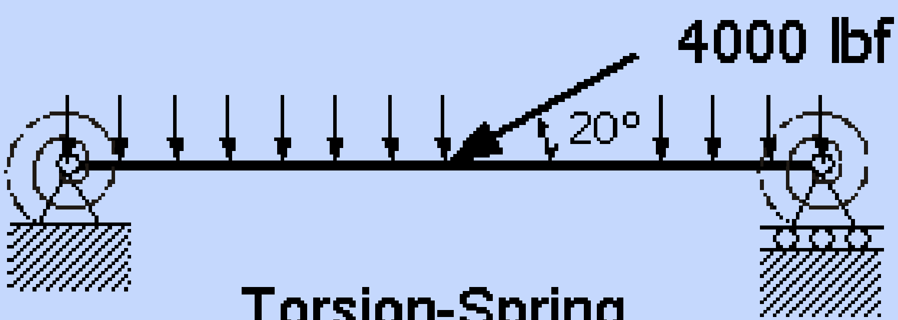
- **Maximum length of open excavation**
- **Clamping force and means**
- **Axial hold force (resists sliding of assembly)**

Entry Fitting – Mathematical Analyses

- Maximum length of open excavated section must be determined based on
  - distributed load (pipe weight)
  - concentrated load (CT injection force)



Unsupported Open Section



Torsion-Spring

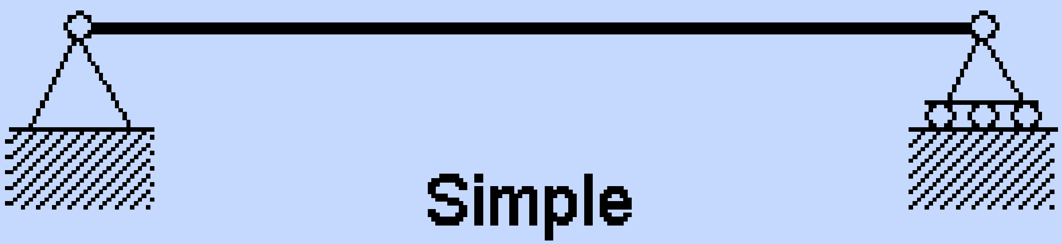
Entry Fitting – Mathematical Analyses

- **Case 1 – pipe ends assumed to be simply supported**
  - **Maximum bending moment at center:**

$$M = \frac{1}{8}WL^2 + \frac{1}{4}PL$$

  - **Maximum tensile stress:**

$$\sigma = \frac{MD}{2I}$$



  - **Maximum length:**

$$\frac{DW}{16I}L^2 + \frac{DP}{8I}L - \sigma_u = 0$$

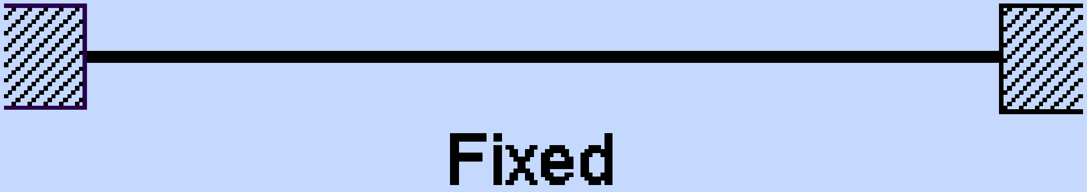
Entry Fitting – Mathematical Analyses

- Case 2 – pipe ends assumed to be fixed
  - Maximum bending moment at center:

$$M = \frac{1}{24} W L^2 + \frac{1}{8} P L$$

  - Maximum tensile stress:

$$\sigma = \frac{MD}{2I}$$



  - Maximum length:

$$\frac{DW}{48I} L^2 + \frac{DP}{16I} L - \sigma_u = 0$$

Entry Fitting – Mathematical Analyses

- **Actual length limit will fall between Case 1 (simply supported ends) and Case 2 (fixed ends)**

Cast-Iron Pipe OD	Wall	Minimum Length (Simple)	Maximum Length (Fixed)
4.8”	0.35”	17.9’	34.8’
4.8”	0.50”	21.8’	41.8’
9.05”	0.41”	52.3’	95.8’
9.05”	0.63”	58.3’	105.1’
13.2”	0.48”	79.7’	142.1’
13.2”	0.79”	84.1’	148.4’

Entry Fitting – Mathematical Analyses

- **Maximum force on pipe from access fitting**
  - **Bending moment:**

$$M_c = \frac{ND}{2\pi}$$

  - **Bending stress:**

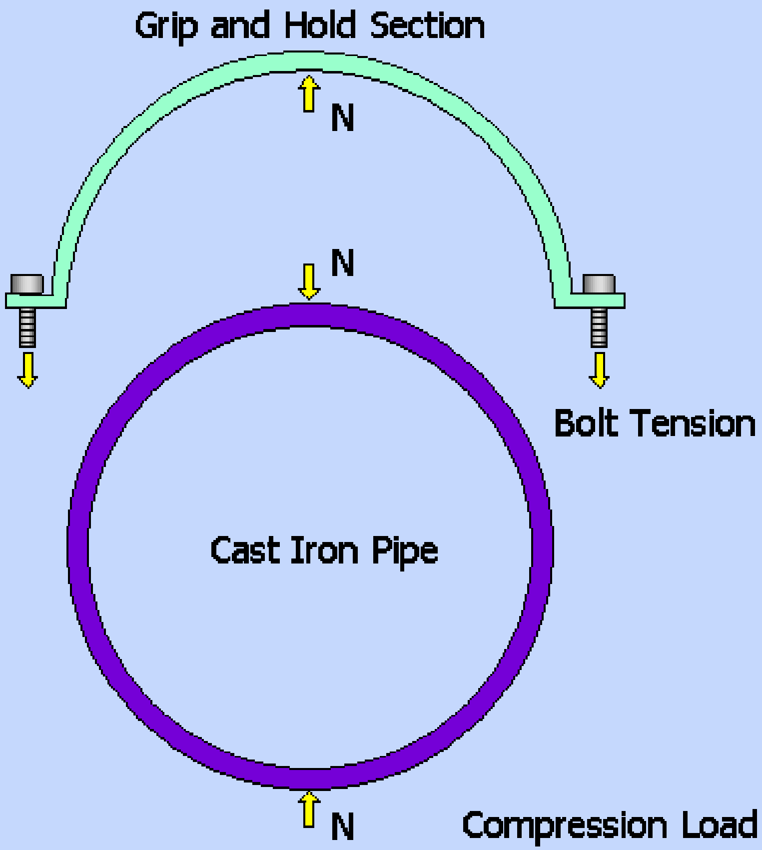
$$\sigma = \frac{M_c H}{2 I_c}$$

  - **Maximum compression load:**

$$N = \frac{4\pi I_c \sigma_y}{HD}$$

  - **Holding force:**

F = 2 f N (x 2 fittings)



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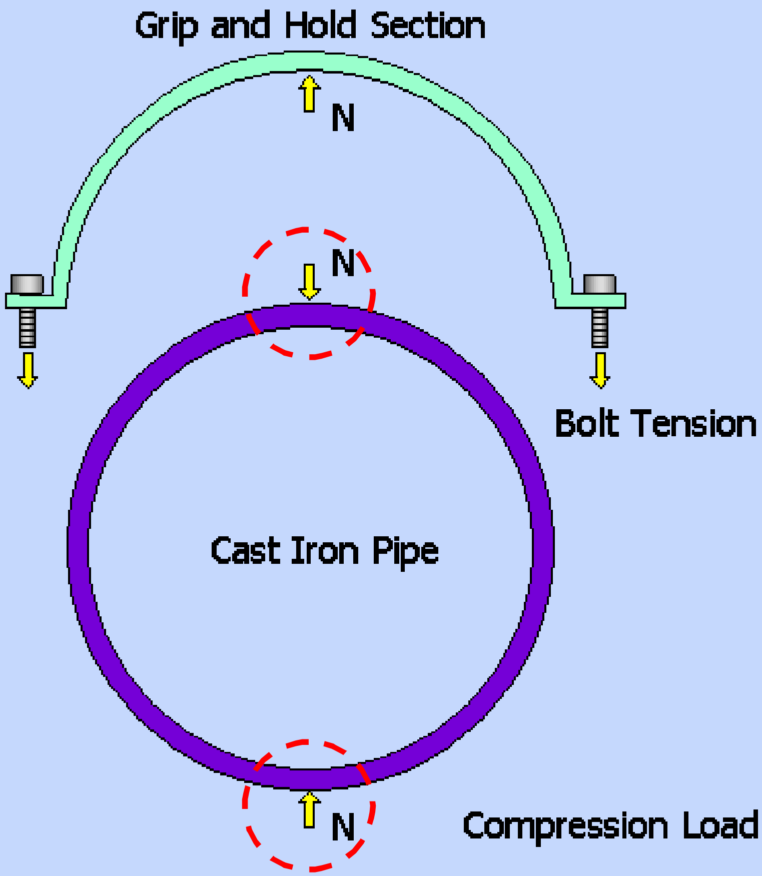
Entry Fitting – Mathematical Analyses

- For worst-case design, assume entry fitting contacts out-of-round pipe only at two points
- Maximum point load the pipe can support limits the axial grip capacity of entry fitting

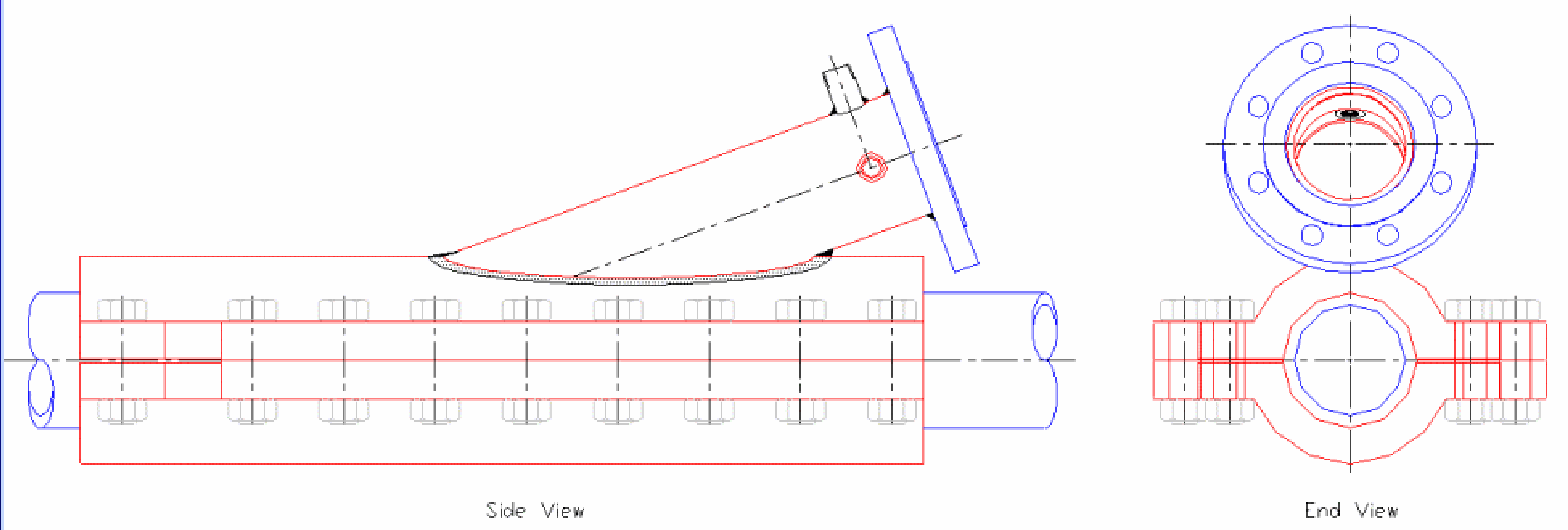


Entry Fitting – Mathematical Analyses

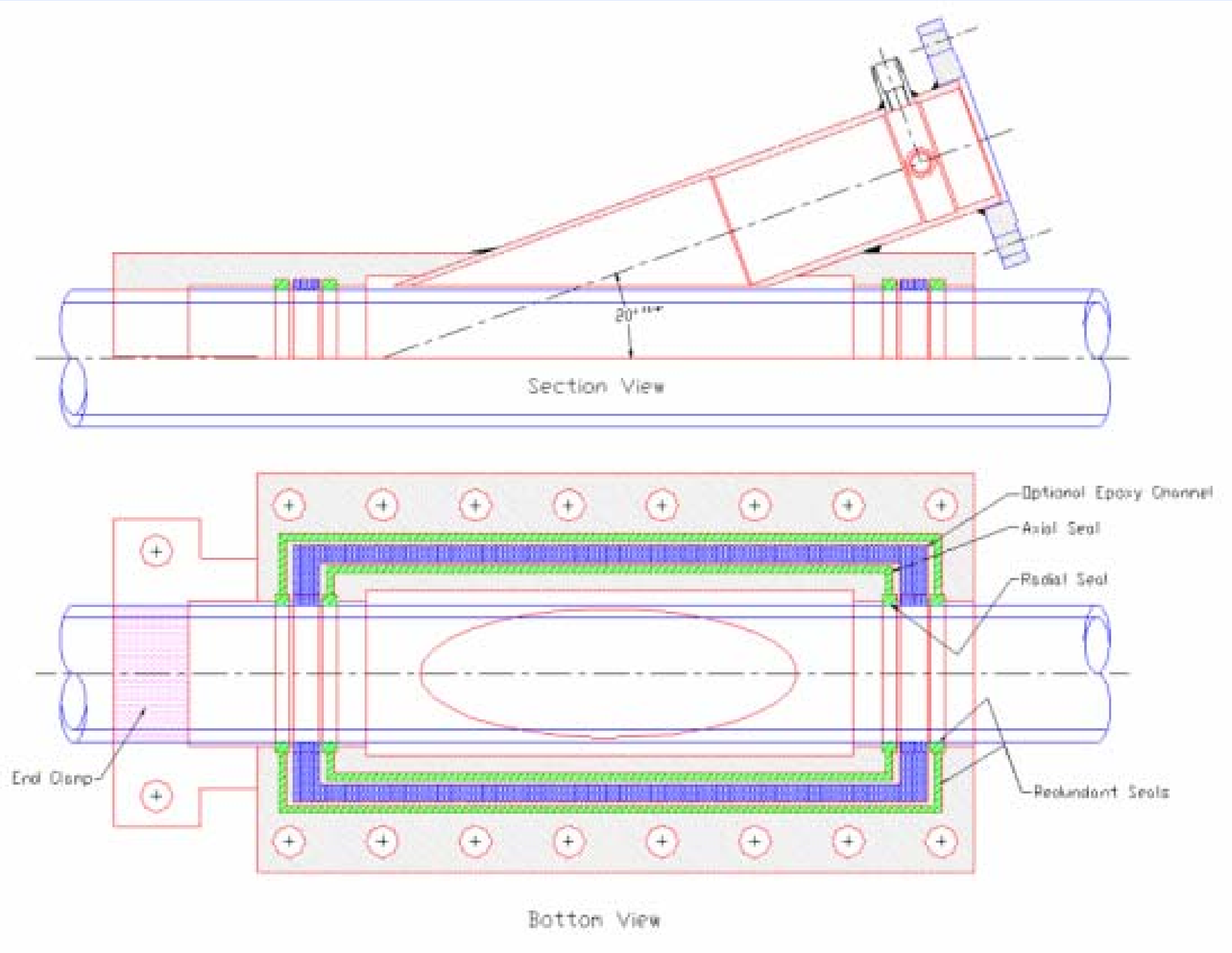
- **Required axial holding force is less than 100 lb**

Cast-Iron Pipe OD (in.)	Wall (in.)	Maximum Point Load (lbf)	Axial Hold Force (lbf)
4.8	0.35	481	770
4.8	0.50	982	1571
9.05	0.41	350	560
9.05	0.63	827	1323
13.2	0.48	329	526
13.2	0.79	891	1426

Entry Fitting for Accessing Pipe



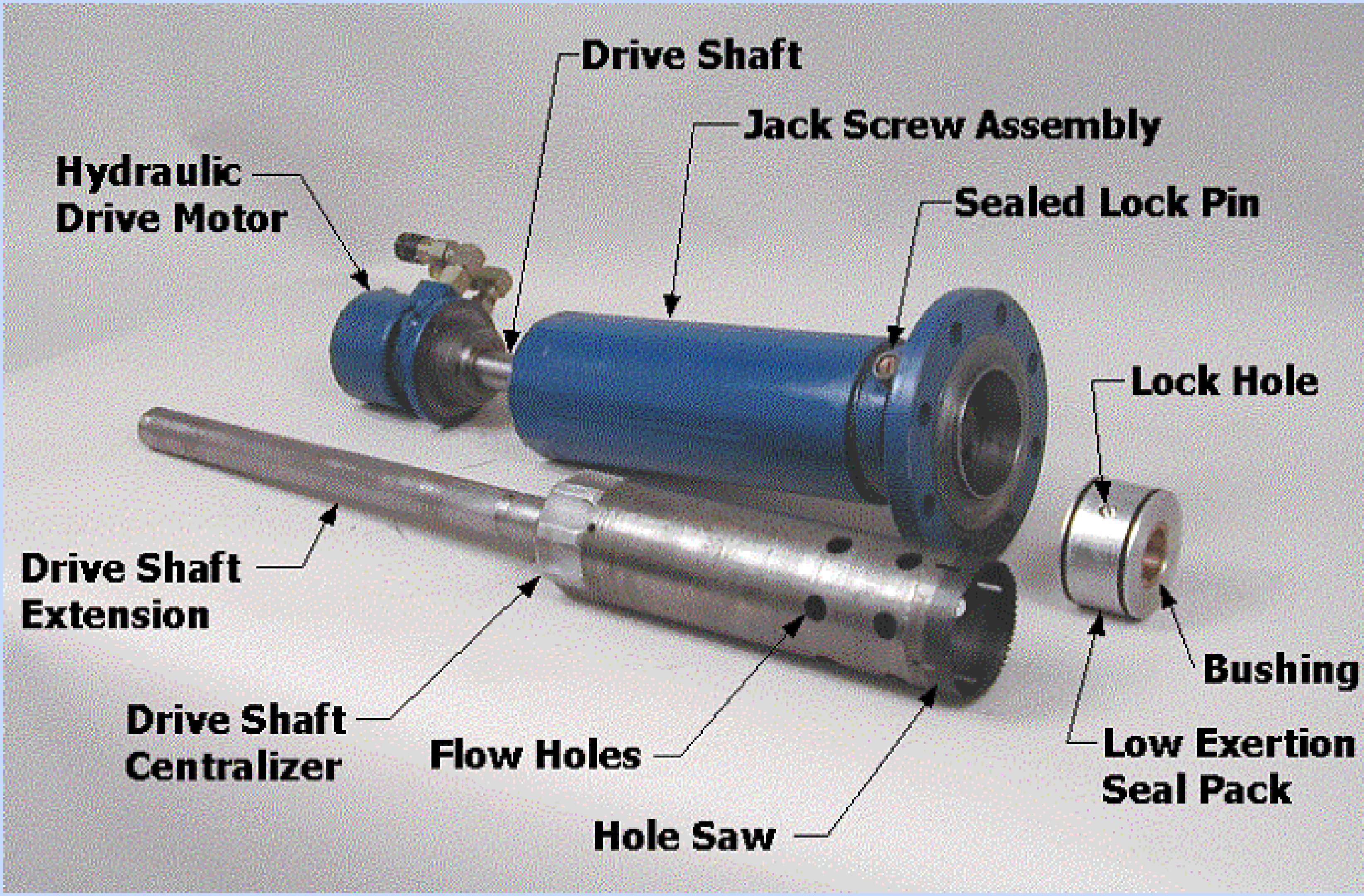
Entry Fitting Seal Design



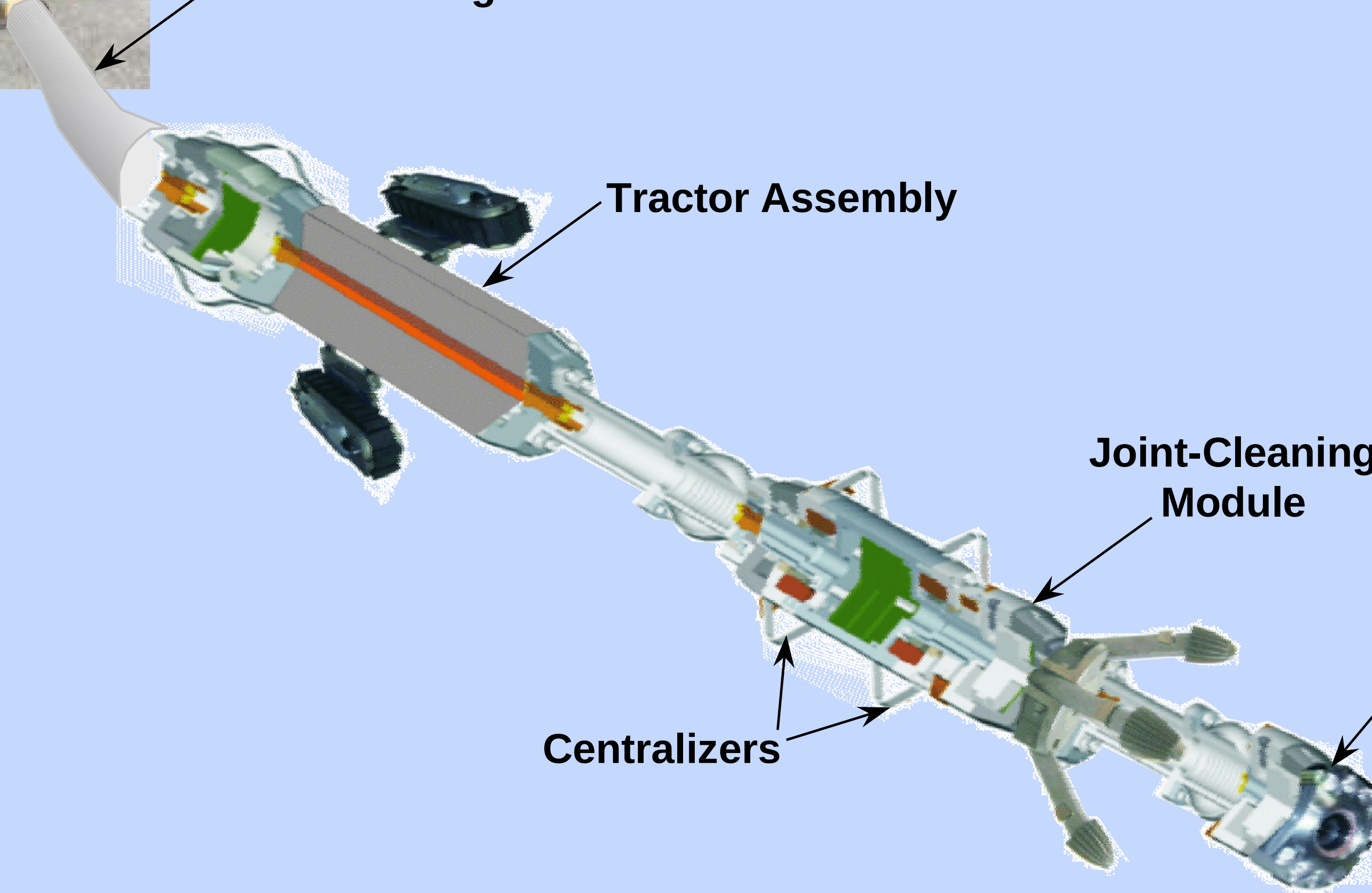
Entry Fitting – Next Steps

- **Review proposed design with fitting manufacturers (mechanical design, compatibility of materials to gas service, etc…)**
- **Finalize design for 8- and 12-inch pipe**
- **Build and test prototypes**

Example Pipe-Cutting Assembly



Inspection/Joint Cleaning Assembly



Camera Functions & Attributes

- Locate each bell and spigot joint to be repaired
- Orient robot for cleaning and patching operations
- Verify success of cleaning and patching operations
- Identify obstructions to movement

Camera Functions & Attributes

- Provide sufficient visual detail and quality
- Operate in wide range of pipe sizes
- Small assembly for ease of entry into and movement within gas mains
- Safe operation (most likely explosion-proof rating)

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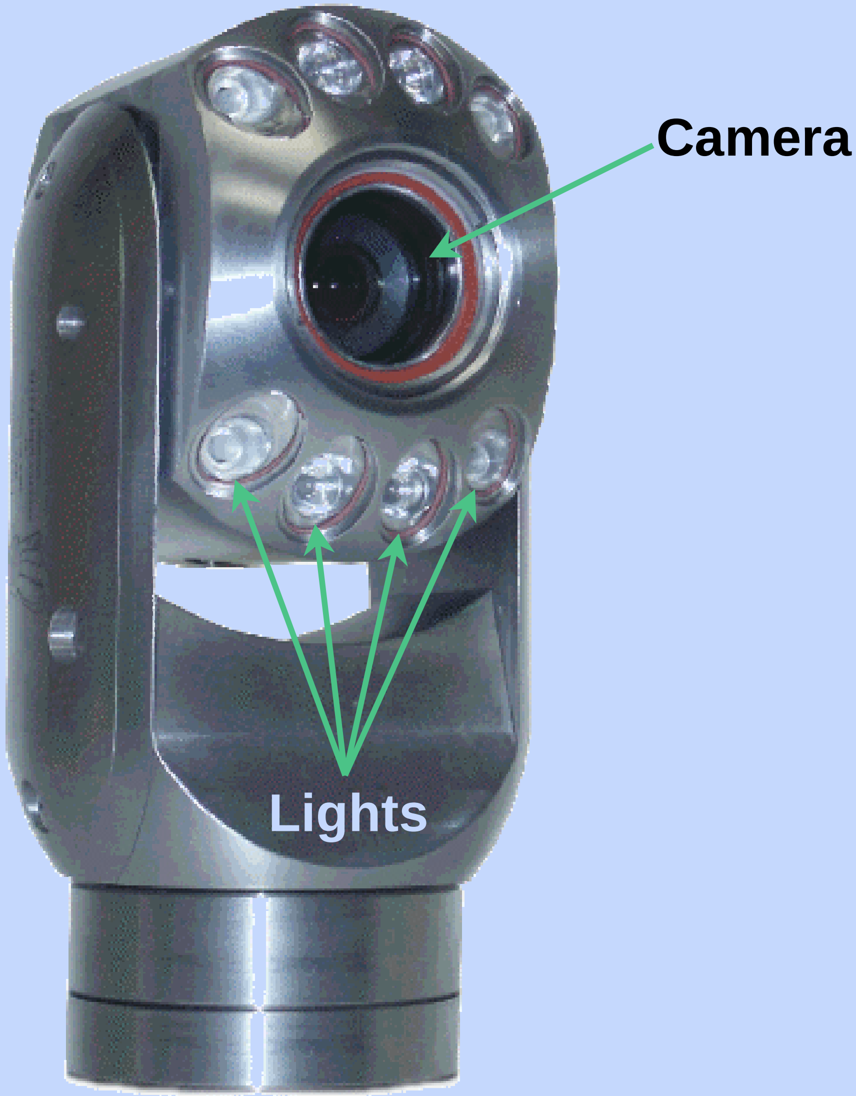
Pan/Tilt/Zoom (PTZ) Camera



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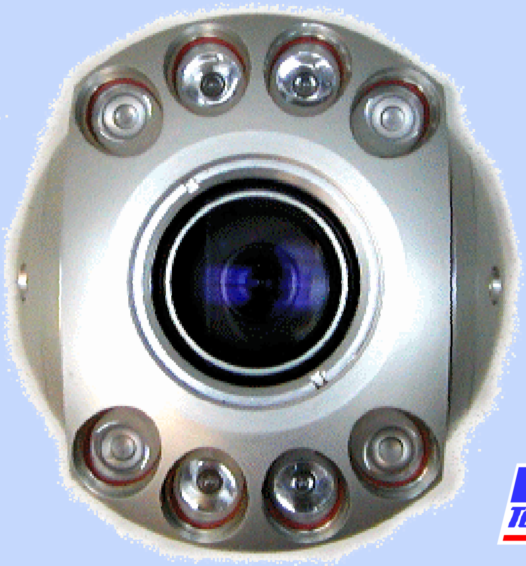
Pan/Tilt/Zoom (PTZ) Camera

- **Maximum OD – 4”**
- **Length – 10.7”**
- **Weight – 7 lb**
- **Light source – eight 6-W argon bulbs**
- **Power requirements (preliminary)**
  - **Camera – 250-300 mA @ 12 V**
  - **Pan/Tilt – 500 mA @ 26 V**
  - **Lights – 4.2 A @ 12 V**



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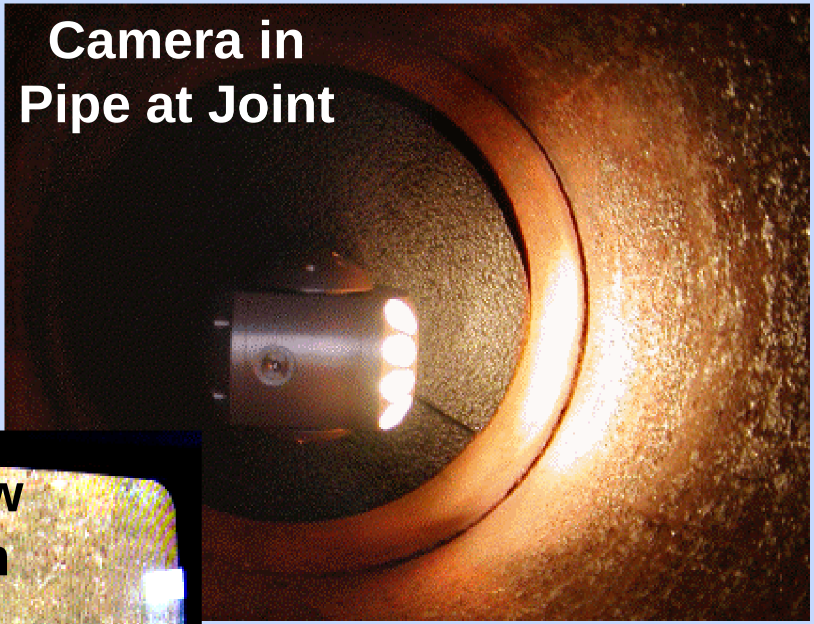
Pan/Tilt/Zoom (PTZ) Camera



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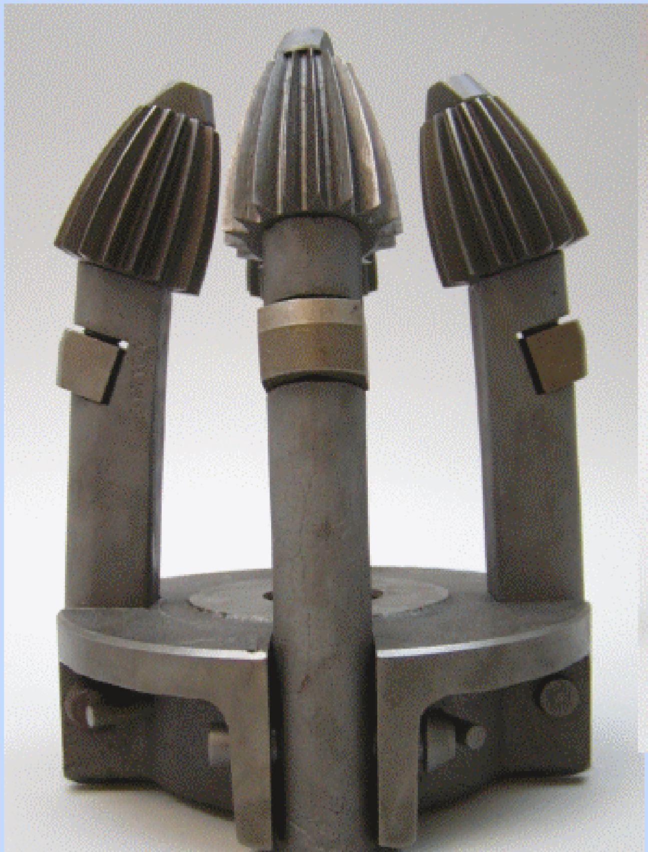
Cleaning Assembly Functions & Attributes

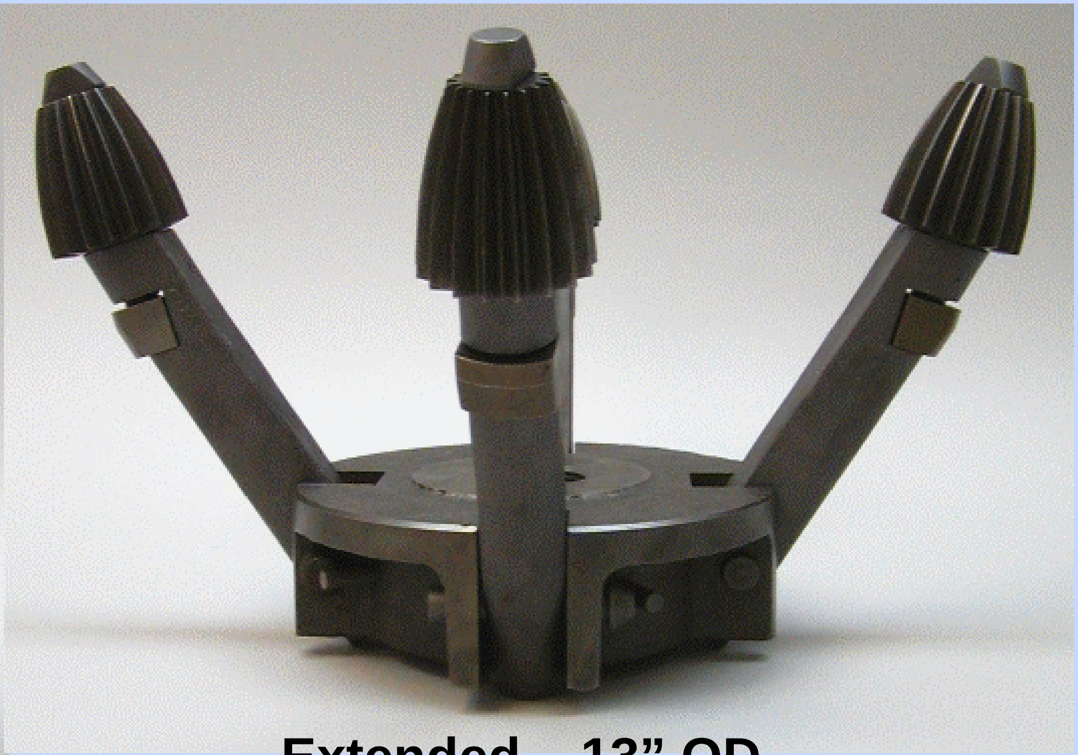
- **Cleaning assembly required to clean debris from bell and spigot joints**
- **Must be capable of loosening both soft and hard debris**
- **Collapsible to minimize size of entry hole cut in main**

Cleaning Assembly – Preliminary Design

- **Four-arm joint-cleaning assembly**



Collapsed – 6.4” OD



Extended – 13” OD

Coiled Tubing Functions

- Mechanical push/pull member for primary locomotion
- Houses multi-conductor e-line for power and data communications between surface and in-pipe robot elements
- Assures robot retrieval from pipe

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Coiled Tubing Mathematical Analysis

- Buckling calculations
- Variables
  - Tubing dimensions (OD and wall thickness)
  - Gas main ID
  - Robot end load
  - Friction factor

Coiled Tubing Buckling Limits

- **Maximum lateral reach of system from pipe entry point is dictated by CT buckling**
- **Maximum lateral reach is:**

$$L = \frac{F - B}{f W}$$

where F = critical buckling load

B = load of bottom-hole assembly

f = friction factor

W = weight of CT per unit length

Coiled Tubing Buckling Limits

- **Critical buckling load, F, is defined as onset of helical buckling:**

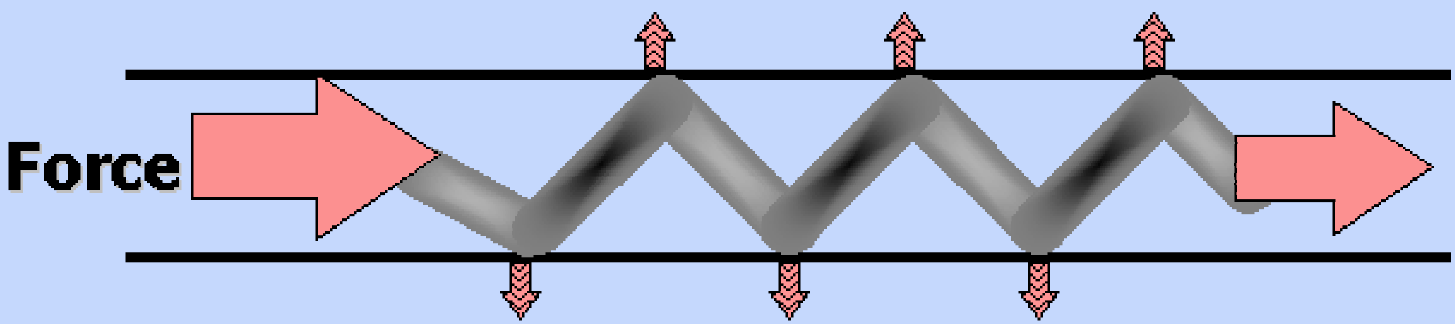
$$F_{hel} = 2\sqrt{2}\left(\frac{EIW\sin\theta}{r}\right)^{1/2}$$

where E = elastic modulus of CT

I = moment of inertia of CT

W = weight of CT per unit length

r = radial clearance between CT and pipe



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Coiled Tubing Buckling Limits

- **Maximum lateral reach was compared for:**
  - **CT OD (7/8, 1 and 1-1/4 in.)**
  - **CT wall thickness**
  - **Gas main OD (12, 18 and 24 in.)**
  - **Friction factor (0.25 and 0.35)**
  - **BHA load dead weight (0, 25, and 50 lb)**
  - **BHA load with tractor (-100 and -200 lb)**

Coiled Tubing Maximum Reach

- **For friction factor = 0.25**

CT OD (in.)	BHA Load (lbf)	Maximum Lateral Reach (ft)		
		12-in. Pipe	18-in. Pipe	24-in. Pipe
7/8	25	1016	794	667
1	25	1219	961	812
1-1/4	25	1613	1278	1087
7/8	-100	1647	1426	1297
1	-100	1730	1471	1322
1-1/4	-100	1963	1628	1437

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Coiled Tubing Maximum Reach

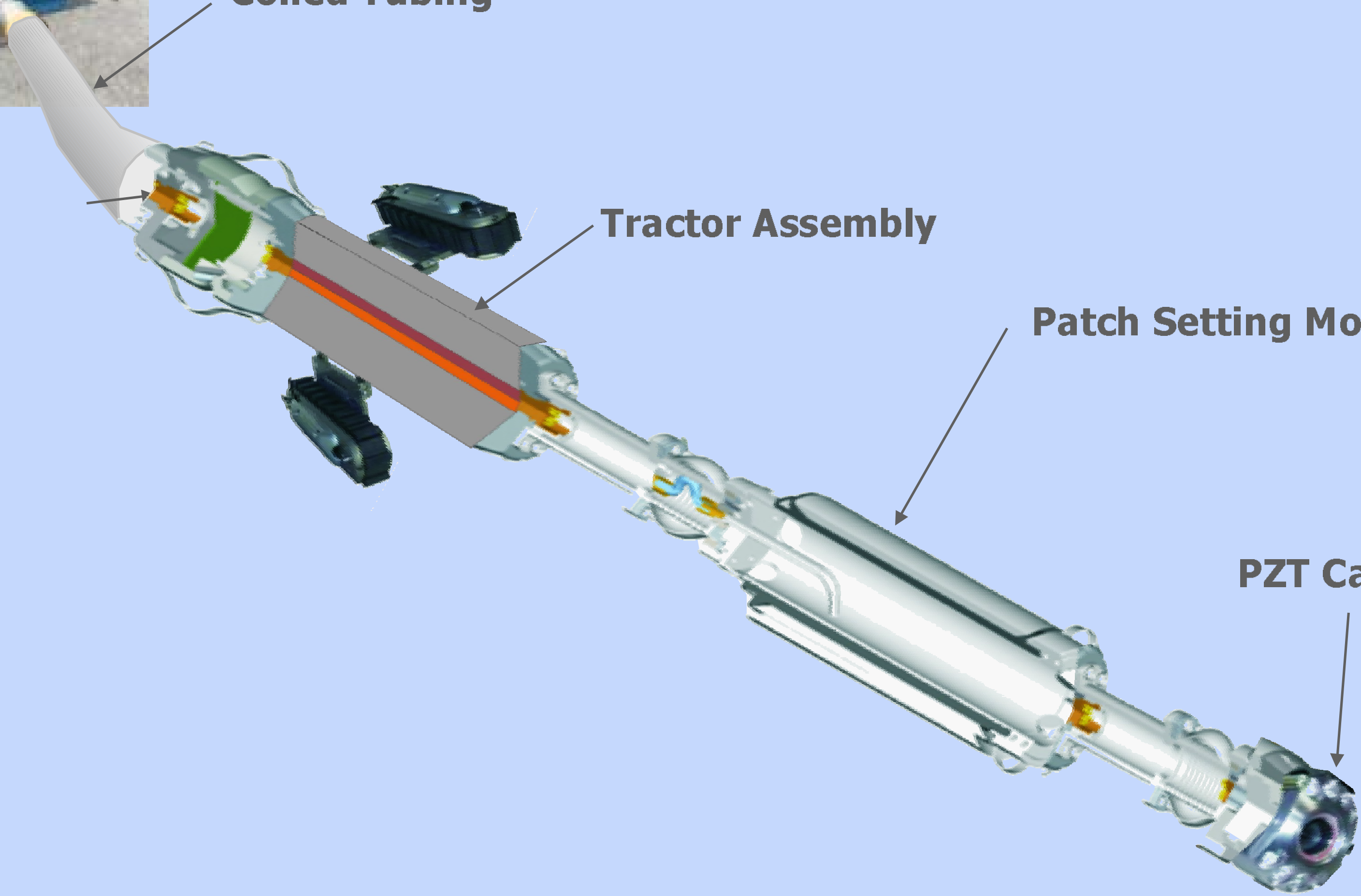
- **For friction factor = 0.35**

CT OD (in.)	BHA Load (lbf)	Maximum Lateral Reach (ft)		
		12-in. Pipe	18-in. Pipe	24-in. Pipe
7/8	25	726	567	476
1	25	871	686	580
1-1/4	25	1152	913	776
7/8	-100	1177	1018	927
1	-100	1236	1051	944
1-1/4	-100	1402	1163	1026

Coiled Tubing Maximum Reach

- Reach is greater for:
  - Smaller gas main ID
  - Larger CT OD
  - Lower friction factor
  - Higher downhole tractor pull forces
- Other techniques to increase reach:
  - Use tapered CT strings (thinner-wall CT downhole and thicker-wall CT near the surface equipment)
  - Add rollers to the BHA to reduce friction

Patch-Setting Assembly



Seal Sleeve Functions & Attributes

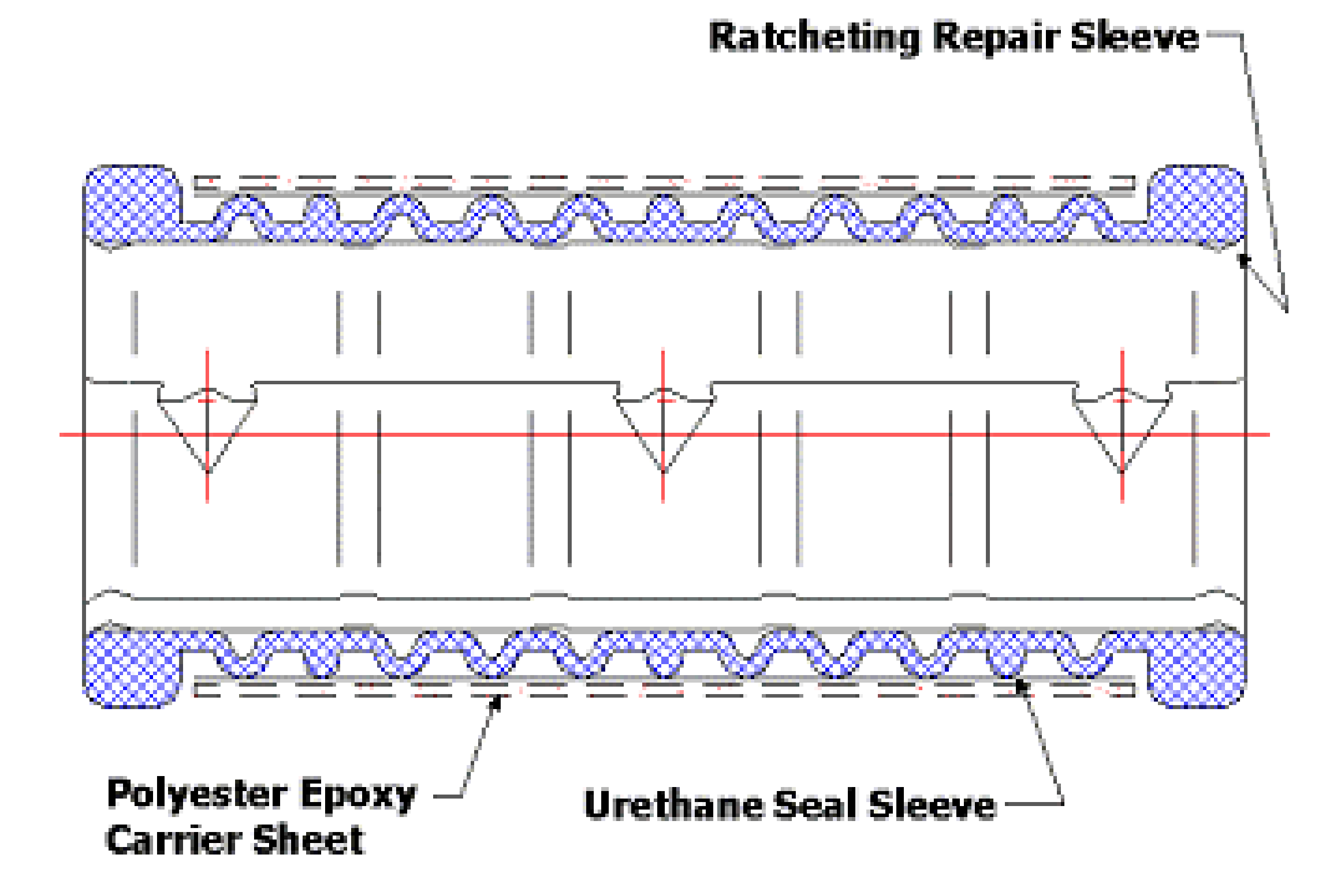
- Seal/close leak paths in bell and spigot joints under live conditions
- Maintain seal integrity under bell and spigot relative movement
- Compensate for variations in pipe ID
- Provide mechanical reinforcement

Seal Sleeve Functions & Attributes

- Provide seal redundancy
- Be tolerant of rigors imposed by travel through debris-laden mains
- Have delivery diameter significantly smaller than expanded/installed diameter for ease of delivery
- Minimize complexity of installation

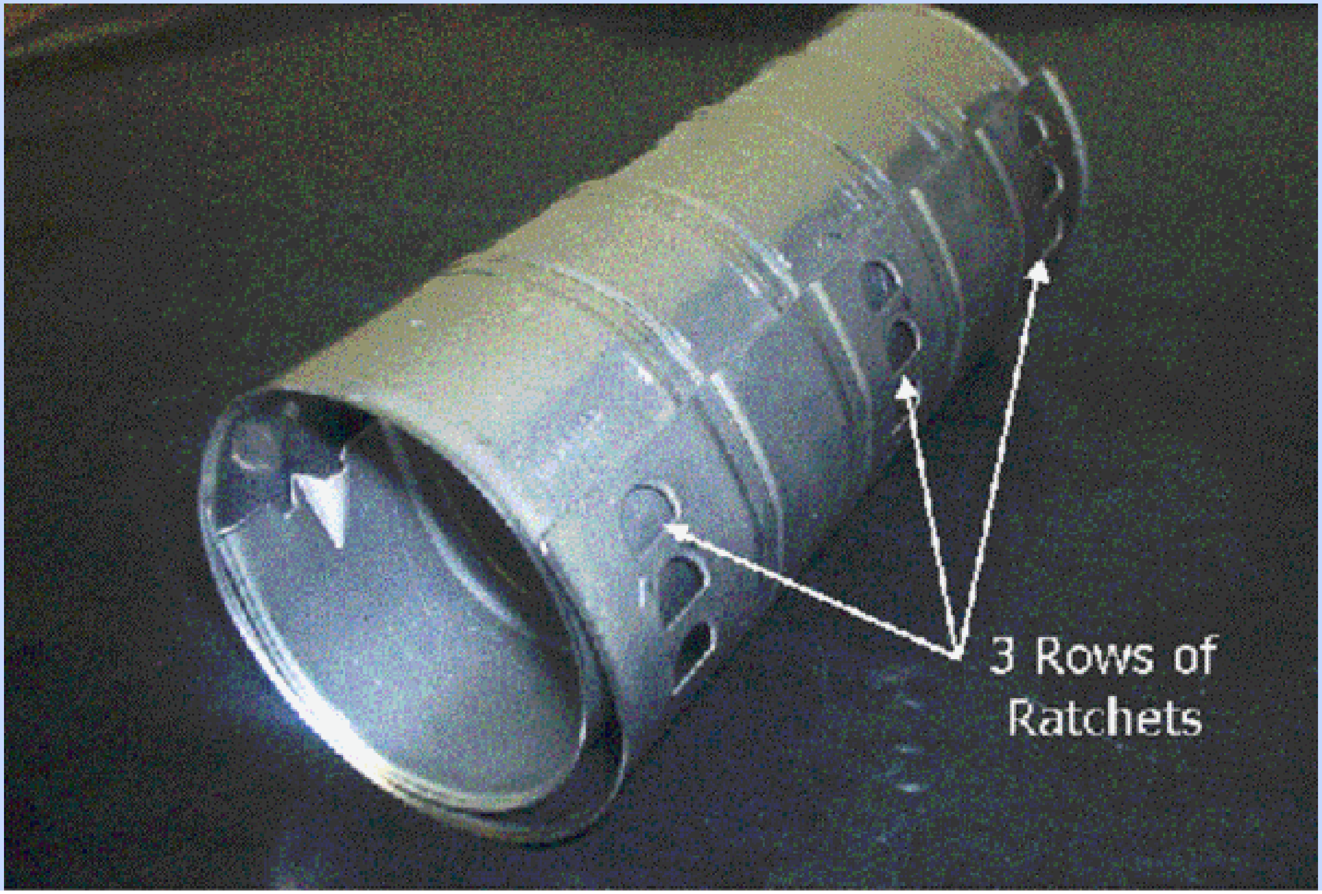
Seal Sleeve – Preliminary Design

- **New sleeve design**



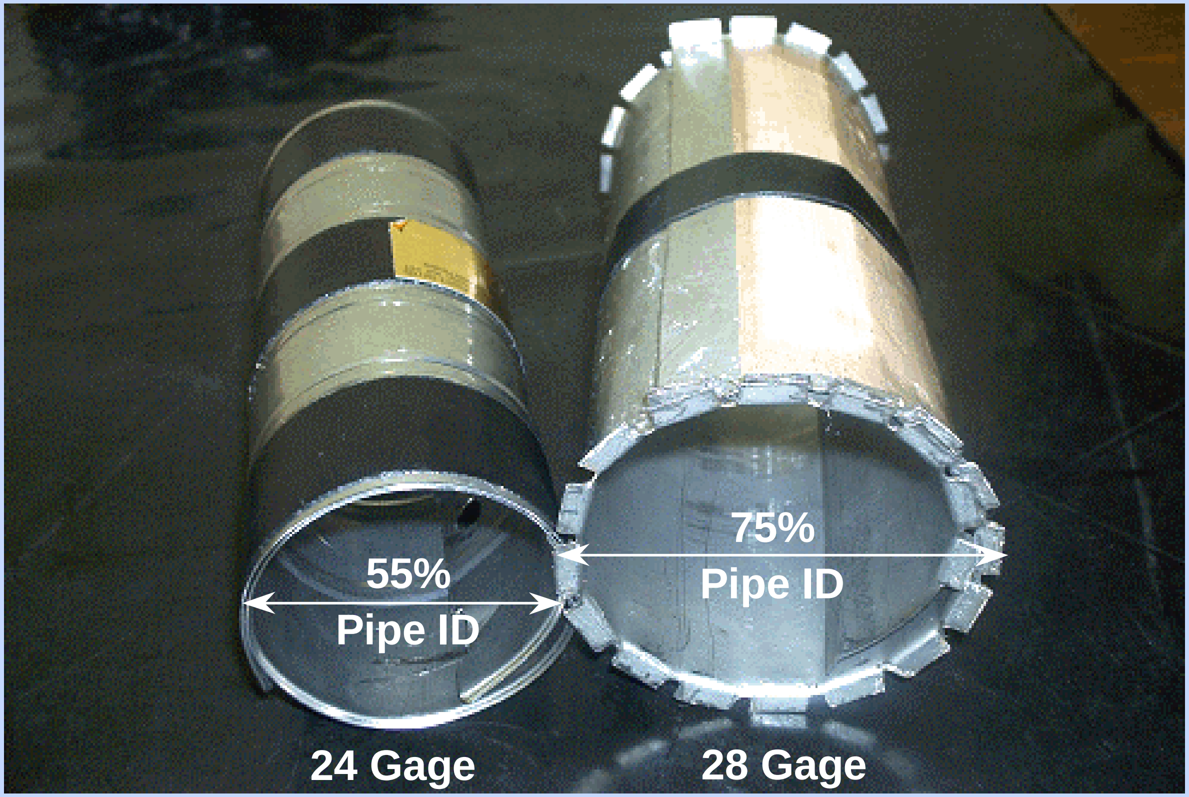
Seal Sleeve – Preliminary Design

- **New sleeve design – ratchets allow locking in ID variations up to 0.50 inches**



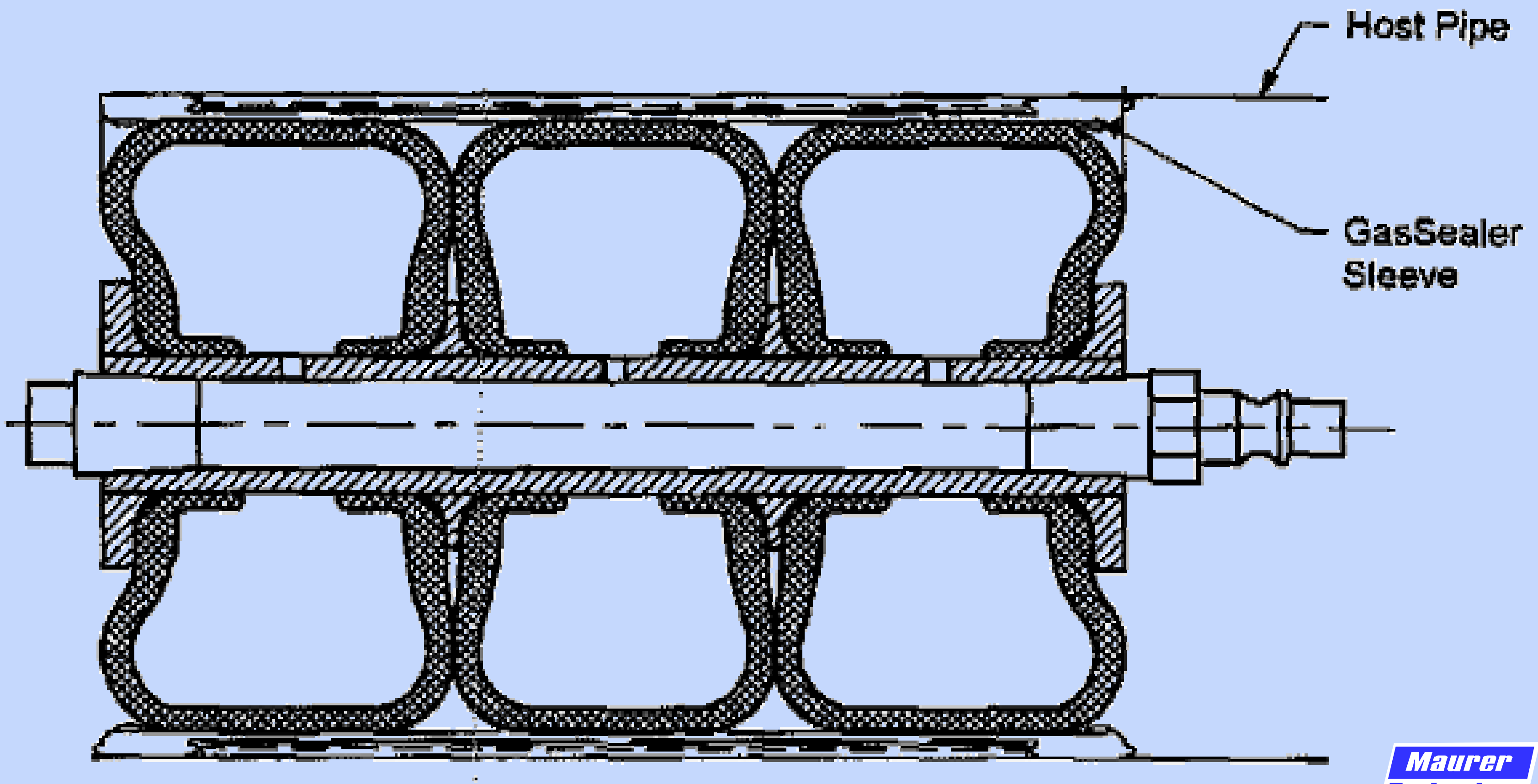
Seal Sleeve – Preliminary Design

- Coiled OD comparison between new 24-gage and previous 28-gage sleeve material



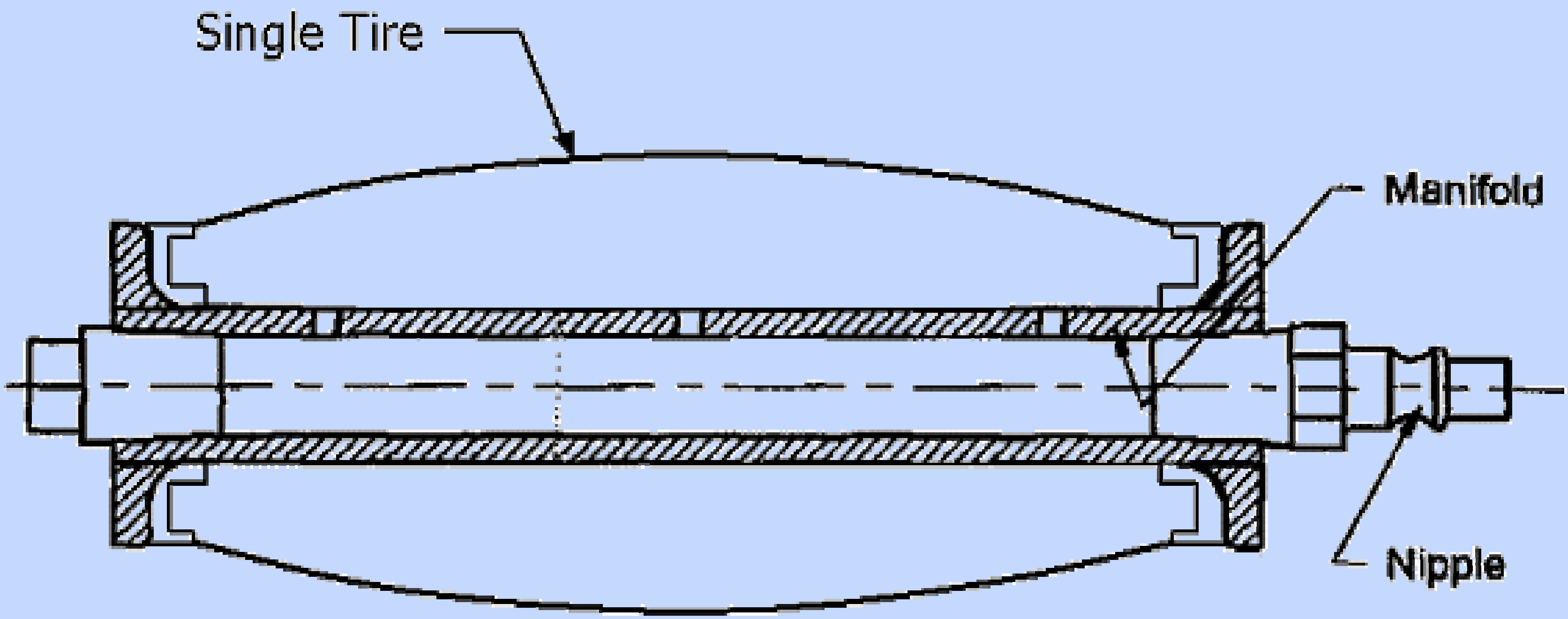
Seal Sleeve Expander – Preliminary Design

- **Sleeve expander – three-chamber design**



Seal Sleeve Expander – Preliminary Design

- **Sleeve expander – one-chamber design**



Summary of Project Status

- **Basic designs have been developed for:**
  - **Pipe-access fitting**
  - **Coiled-tubing string**
  - **Pipe-cleaning assembly**
  - **Seal sleeves**

Next Steps

- Process questionnaires to Utilities
- Complete design and fabricate prototype repair sleeves; conduct preliminary testing
- Conduct tests of cast-iron wall cleaning system for sizing motor and finalizing cleaner design
- Meet with manufacturers to produce entry fitting

Upcoming Milestones